Casimir-drag force in superfluids

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Recent calculations show that a Casimir-like drag force can exist in Bose-Einstein condensates at zero temperature. The existence of this force has important consequences for our understanding of superfluids in general as well as potential implications for the design of atom lasers.

Superfluidity is the dramatic phenomenon of frictionless flow first observed in liquid helium in 1938 by Kapitza, and it continues to fascinate physicists many decades after its discovery. Superfluids are intimately related to Bose-Einstein condensates (BECs), a novel form of matter first predicted to exist by Satyendra Bose and Albert Einstein in the 1920s. This form of matter is characterized by a large fraction of atoms being in the quantum ground state. Dilute BECs occur very close to absolute zero temperature and it was only in 1995, through an experimental *tour de force*, that they were finally observed in the laboratory. In a number of experiments, researchers have observed dilute atomic BECs to have various characteristics that imply superfluidity, including the measurement of nonclassical moments of inertia, quantized vortices and dissipationless flow.

It is widely accepted that a superfluid flow exhibits a critical velocity below which there is no dissipation. In other words, an object immersed in a superfluid flowing below this critical velocity feels no force despite the fluid's movement. The reasoning is that, at such low speeds, the superfluid would not be able to create any excitations and hence not be able to dissipate energy. Landau first proposed the traditionally accepted explanatory mechanism for the breakdown of superfluid flow; he predicted a critical value for the velocity of superfluid flow above which the flow becomes unstable. However, this mechanism does not account for the presence of quantum fluctuations.

Landau's assertion that there is a critical velocity below which a superfluid flow is not dissipative has been the subject of a large number of analytical studies and numeric simulations that use a mean-field approximation. This approach involves assuming that all flow atoms have the same wavefunction. The equation governing this wavefunction is known as the Gross-Pitaevskii equation and provides a good approximation if the system is at zero temperature and a large fraction of the atoms are condensed. Such mean-field studies have been made on superfluid flows in various geometries. The main lesson from these theoretical mean-field studies, whatever the complicated geometry, is that, if one applies the Landau criterion to the maximum local fluid velocity rather than the bulk flow, Landau's insight was largely correct.

However, compared with experimental findings, Landau's prediction and the mean-field approach fare less well. Experiments using superfluid helium have shown the critical velocity predicted using this mean-field approximation to be significantly higher than that observed. For over sixty years now, scientists have been puzzled by the failure of Landau's predicted critical velocity to match that of experimental observation. Many theoretical research efforts have been made to explain this discrepancy but without satisfying results.

The explanation may lie in correlation effects from atomic interactions, or quantum fluctuations, which Landau did not explicitly address in his phenomenological argument and which are ignored through the mean-field approach. Despite being small compared to the mean field, the quantum fluctuations — which are responsible for quantum depletion of the ground state — have observable effects in dilute BECs. At temperatures far below the critical temperature (at which the Bose gas condenses to form a BEC), the behavior of these fluctuations are described by the nonuniform Bogoliubov-de Gennes equations, which provide a closer approximation to the behavior of the condensate system through the inclusion of atomic-correlation effects.

There is reason to believe that such quantum fluctuations can have an effect on the critical velocity, specifically by producing a drag force on an immersed object. Inspired by the work of Hendrik Casimir who showed in 1948 that quantum fluctuations in an electromagnetic vacuum produce an attractive force between two closely spaced conducting plates in a perfect vacuum, Yves Pomeau and I showed that a similar force should arise between two walls immersed in a dilute BEC due to the quantum fluctuations around the condensate's ground state [1].

Furthering this idea, we showed that, as a result of the scattering of quantum fluctuations, an idealized object in a slow-moving infinitely extended dilute BEC should also feel a slight damping force, which we shall refer to as a "Casimir-drag" force [2]. We modeled the object by a localized potential varying only in the flow direction. The flow was modeled by a three-dimensional weakly interacting BEC at zero temperature. In this system, we showed that such a "Casimir-drag" force exists for any arbitrarily small flow velocity.

Working with a more realistic object, I derived an analytic expression for a force on a weak point impurity arising from the scattering of quantum fluctuations in the same slow-moving, weakly interacting, three-dimensional BEC at zero temperature [3]. In an infinitely extended geometry, I showed this force to be directly proportional to the flow speed and to exist at any arbitrarily small flow velocity, even below Landau's critical velocity. The findings of both the 1-D potential and the point impurity calculations thus show the effective critical velocity of our "ideal" superfluid to be zero.

We recently extended our research to investigate the effect of quantum fluctuations scattering off a rough surface [4], which is an important feature in many superfluid helium experimental setups as well as in experiments on directing Bose-condensed atoms through wave guides near a surface. We discussed the form of the boundary condition for a superfluid moving along a rough surface, taking into account quantum fluctuations. The scattering of quantum fluctuations off surface roughness results in a nonlocal perturbation that changes the nature of the boundary condition, and this has important consequences including the implication of a new critical speed and a temperature difference between a moving superfluid and the boundary (i.e. the presence of a non-zero normal fluid fraction in any superflow).

The existence of this Casimir-drag force leads to a number of interesting consequences. One such arises from discussion of its manifestation in a finite volume, e.g. within the torus of a persistent current experiment. In the latter case, the waves that have scattered off a localized object within that confined space will eventually re-interact with the object. Eventually a steady state is reached in which the effect of the "backscattered" waves cancel out the original Casimir-drag force, and a persistent current establishes itself. Seen in this way, the phenomenon of persistent currents can be thought of as a finite-size effect. One may therefore expect to observe the Casimir-drag force as a transient effect that dies off over a time scale on the order of the length of the system divided by the speed of sound, i.e. the time it takes for the scattering waves to experience the finitude of the system. This time scale provides an observable effect of the theorized Casimir-drag force, the existence of which should thus be verifiable with the persistent BEC-current experiments presently being designed.

One future technological application that is currently receiving great attention, and for which a Casimir-drag force would have important design implications, is the atom laser. Excitement surrounding the creation of atom lasers stems from their potential for application in a variety of areas, from nanotechnology to gravity surveys, and from atom lithography to time measurement using precision atomic clocks. As in the early years of the laser, it is difficult to predict all of the possible applications.

As they are presently conceived, atom lasers draw upon BECs as a source of coherent traveling atoms. The superfluid nature of BECs therefore plays a role in the behavior of the atom laser. To maximize the atom coherence, very low temperatures are desired — precisely the temperature regime in which the Casimir-drag force would be expected to dominate. Since the Casimir-drag force exists in this superfluid system, heating (with its attendant coherence loss) may arise in a previously unanticipated way, an effect that should be accounted for in the conception of atom lasers.

References

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